UCRL-JC-118267 EXT ABS

A SOLAR MODULE FABRICATION PROCESS FOR HALE SOLAR ELECTRIC UAVS

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We describe a fabrication process used to manufacture high power-to-weight-ratio flexible solar array modules for use on high-altitude-long-endurance (HALE) solar-electric unmanned air vehicles (UAVs). A span-loaded flying-wing vehicle, known as the RAPTOR Pathfinder, is being employed as a flying test bed to expand the envelope of solar-powered flight to high altitudes. It requires lightweight flexible solar modules able to endure mechanical stress and adverse environmental conditions. Following extensive flight tests of a first generation module design, second generation modules have achieved power-to-weight ratios of 315 W/kg for 6-mil-thick monofacial silicon solar cells, and over 390 W/kg for bifacial 4.3-mil-thick silicon solar cells. These calculations reflect average module efficiencies of 15.3% (6-mil) and 14.6% (4.3-mil) obtained from electrical tests performed by Spectrolab under AM0 global conditions at 25°C, and include weight contributions from all module components (solar cells, lamination material, bypass diodes, interconnect wires, and adhesive tape used to attach the modules to the wing). In contrast to normal solar cell applications, the Pathfinder module power output during operation will actually be higher due to cooler operating temperatures at higher altitudes, and a bifacial component which increases power output by an average of 15% for the bifacial modules. Module power-to-weight ratios in excess of 450W/kg are predicted under these conditions. The laminate materials, Tedlar and silicon, have been chosen to minimize UV degradation, withstand the extreme thermal variations imposed by long-endurance high-altitude flight, and accommodate the flexing of the wing. The fabrication, testing, and performance of 32 m^2 of these modules will be described.

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Introduction

The RAPTOR Pathfinder solar electric airplane is serving as a technology integration platform to enable long endurance high altitude flight for weeks or months. The airplane has a 98 ft wingspan with an 8 ft chord, and was originally built and flown in 1983 by AeroVironment Inc. Flight altitudes exceeding 10,000 ft were achieved using Ag/Zn batteries as the power source. The flight envelope of the original aircraft has been expanded for high-altitude flight through major upgrades to its structure and electric propulsion systems. In addition, the plane has been converted to solar electric powered flight by covering the upper wing skin with lightweight flexible solar array modules. First generation modules were used to provide approximately one-half of the electrical power in a series of flight tests which took place between 10/93 and 1/94. This paper describes the development of a lightweight flexible solar array module fabrication process used on 32 m^2 of second generation solar modules.

Solar Cell, Interconnect, and Module Performance

The solar cells are made from single crystal Cz silicon that is thinned to 6 mils for the monofacial cells and 4.3 mils for the bifacial cells. Both are type K-6 solar cells with diffused Al and ^{11}B implanted back surface fields for the mono- and bifacial cells, respectively. Average efficiencies for the 6.73cm x 6.98cm solar cells are 15.7% for the 6 mil cells and 15.0% for the 4.3 mil cells (frontside illumination only).

The interconnects have been chosen to have low resistance while being lightweight and flexible. We use 2 mil thick Ag etched-mesh interconnects which electrically interconnect the solar cells along each edge. Modules made using these interconnects have been mechanically tested in our wing stress simulation apparatus. This apparatus simulates Pathfinder take off, landing, and up to a 5g load on the wing by subjecting the module to ±45 mil tension-compression cycles over a 20 inch rib bay section. No electrical failures have been observed after over 20,000 tension-compression cycles.

The solar cells are interconnected into strings of 7 cells per row with 20 mil spacings between cells and 8 rows per module (1 module = 7 x 8 array of cells). Each module is 47.5cm x 56cm (0.268m^2). The average array aperture-area efficiencies as measured by Spectrolab under AM0 global (25°C) testing conditions are 15.3% for the 6 mil and 14.6% for the 4.3 mil (frontside illumination only) modules. Electrical performance for the modules will be better than this because of the low operating temperatures expected in the 40,000 to 80,000 ft altitude range predicted for Pathfinder (summer 1994). In addition, the bifacial modules will collect Albedo radiation (a 15% enhancement) because the Pathfinder wing is transparent.

Solar Array Laminate Structure and Lamination Process

The laminate structure consists of two fluoropolymer Tedlar/silicone adhesive sandwiched layers that encapsulate the solar cells. The result is a sealed planar solar cell array laminate structure. The fluoropolymers are ideally suited for this application because they are: virtually chemically inert, highly transmissive in the visible spectrum, dimensionally stable for temperatures between -70°C to 107°C, highly abrasion resistant, and exhibit very little UV degradation. We have chosen very thin layers of each laminate in order to fabricate high power to weight ratio solar array modules. The Tedlar film is 12.5µm (0.5 mil), and the unsupported silicone adhesive film is 50µm (2 mils). Together they add up to 178 gm/m^2 (0.036 lb/ft^2) for the top and bottom layers.

The process involves laminating the electrically connected solar cells between the top and bottom Tedlar/silicone adhesive layers. This encapsulates the silicon solar cells as shown in Fig. 1. The process is best described by illustration (Fig. 2). As the release liner is removed, the

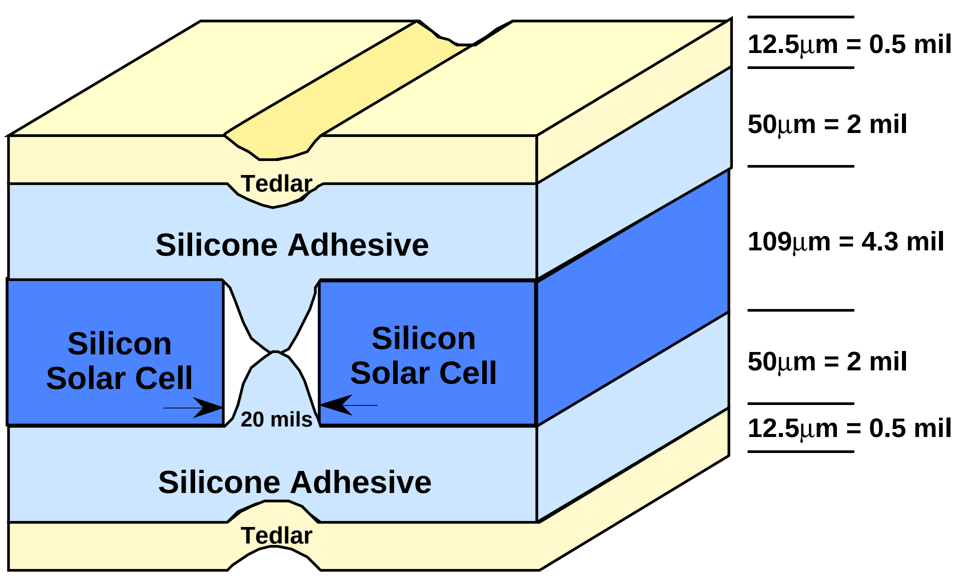

Fig. 1 - Solar array module structure with sealed solar cells. Silicon solar cell thicknesses of 6 mil (152µm) and 4.3 mil (109µm) are used in this work.

top and bottom laminate layers are fed between the laminating rollers. The electrically connected solar cells are then fed through the apparatus and sealed by the top and bottom laminate layers. The cells pass through the apparatus twice. The first pass is at room temperature and causes the solar cells to be laminated to the top and bottom layers. The second pass is at 100°F (37°C) and causes the silicone adhesive layers to reflow and seal the solar array module.

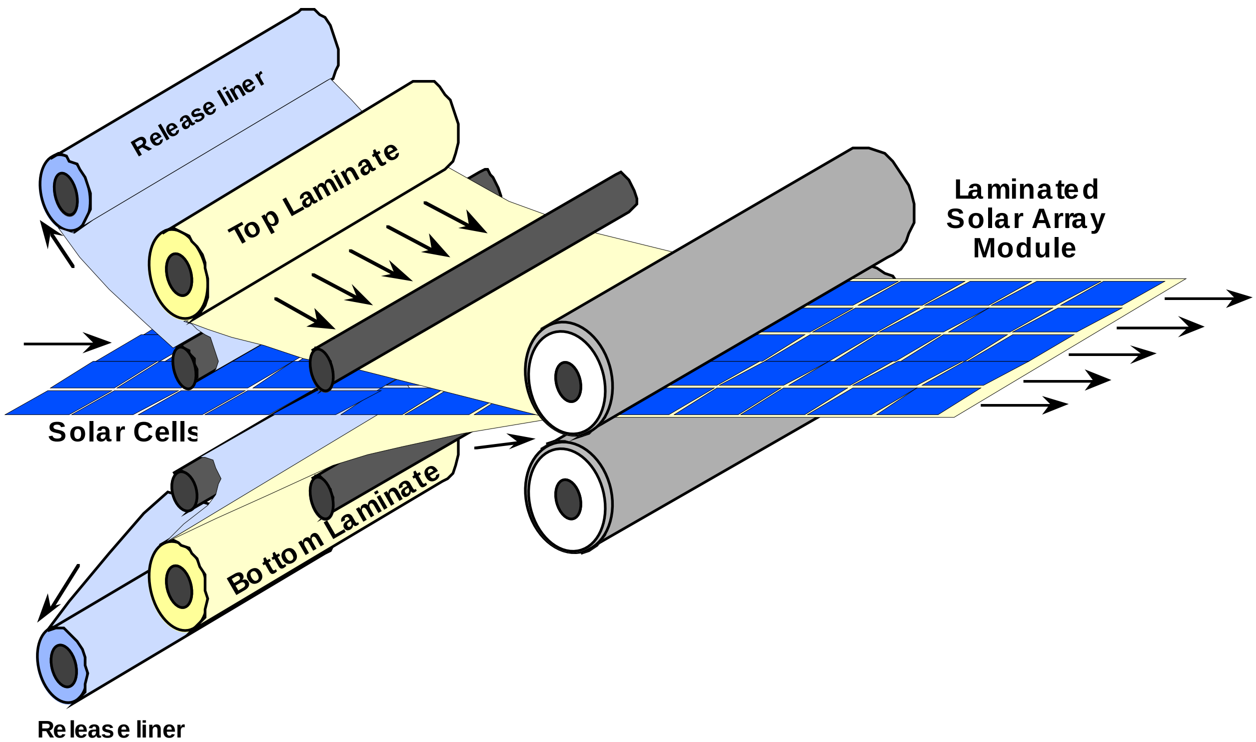

Fig. 2 - Schematic of array lamination process. The polyethylene release liners are removed and the top and bottom laminate layers are fed to the laminating rollers. The electrically connected solar cells are then fed through the rollers to laminate them into a solar array module.

Summary
We have developed an array lamination process to fabricate high power-to-weight ratio solar modules. This process involves first electrically interconnecting the solar cells with a flexible interconnect, followed by laminating between two Tedlar/silicone adhesive sandwiched layers. The modules have achieved 315 W/kg (6-mil) and 390 W/kg (4.3-mil).

Acknowledgments
The work was performed under the auspices of the U.S. Department of Energy under Contract W-7405-Eng-48. The authors would like to thank Mark Cohen, Jim Daley, Bob Curtin, Ray Morgan of AeroVironment, Inc. for valuable insights and suggestions, and Eric Davis for help setting up the module testing.

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We wish to submit this paper to category 6E (Space Systems, Conventional and Novel Array Designs). We also prefer an oral presentation.